Rapid Prediction of Installed Jet Noise From RANS

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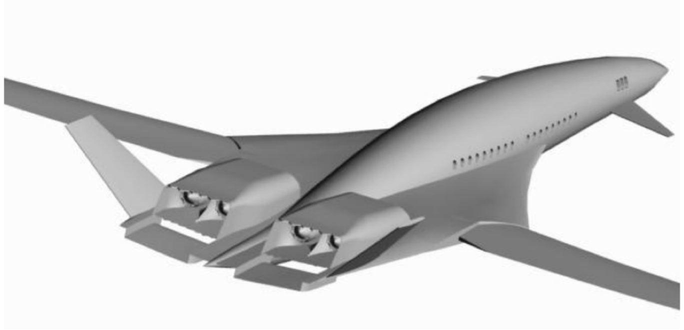
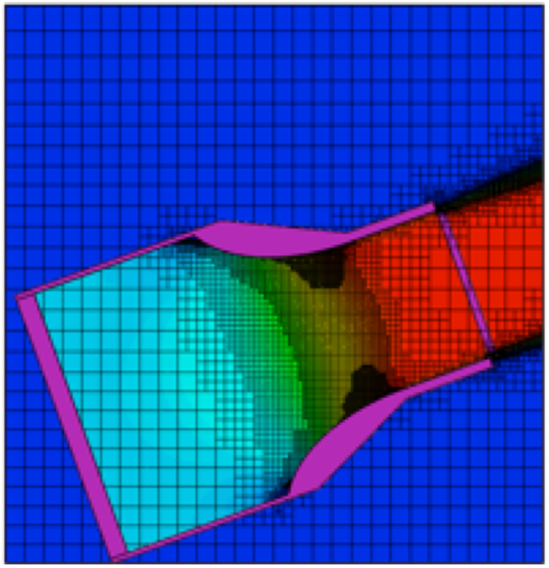
and NASA collaborators in obtaining flow and acoustic data.

Motivation

- Need for speed in evaluating exhaust concepts for noise
  - Empirical – Fast; Can't account for strange nozzle geometries
  - RANS – Quick enough? Steady acoustic sources, no resonances
  - LES – Slow; Too cumbersome
- How to speed up RANS-based methods?
  - Make import/creation of geometry easy → Tie to solid modeling software
  - Automate grid generation, refinement → Cartesian methods
  - Make acoustic code robust, fast.
- Acoustic analogy codes for RANS typically have two components—source and propagation (Green function)
  - Solving for Green's function is expensive, requires smooth solutions, different grids than RANS
  - Adding surfaces further complicates Green's function solutions

- Looking for 'good enough' answers for design work—noise is measured in dB!





Motivation

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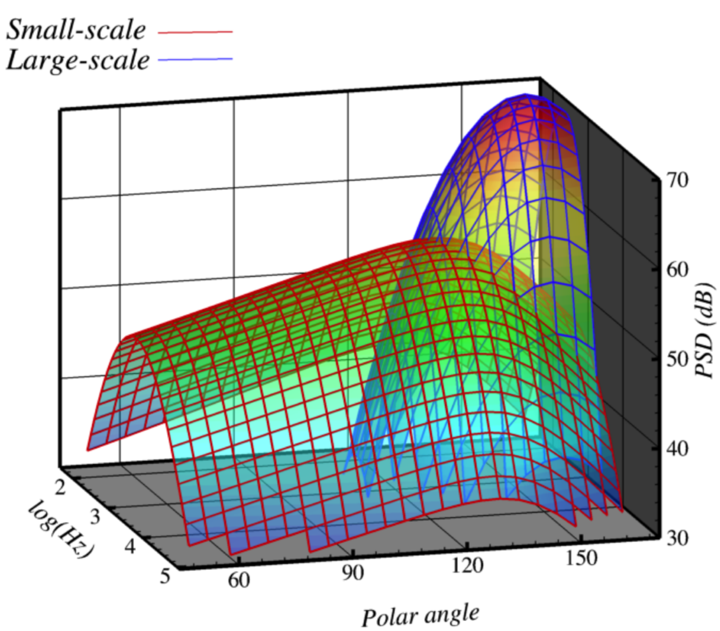
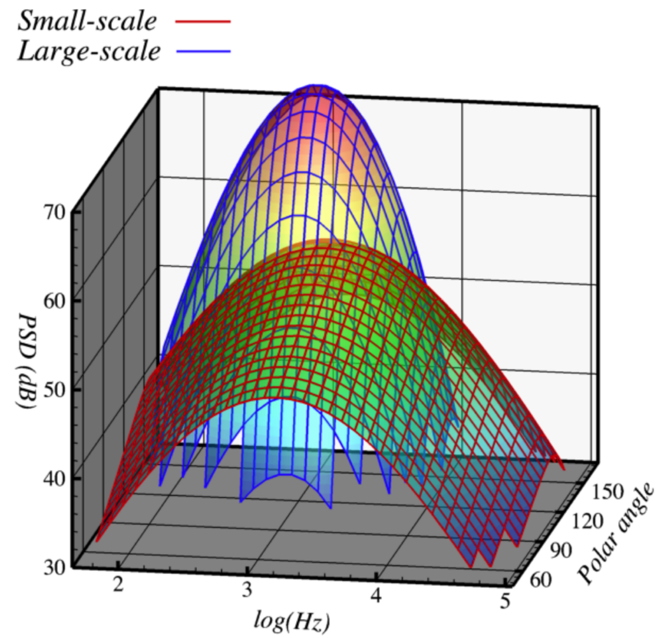
Heuristic two-component model

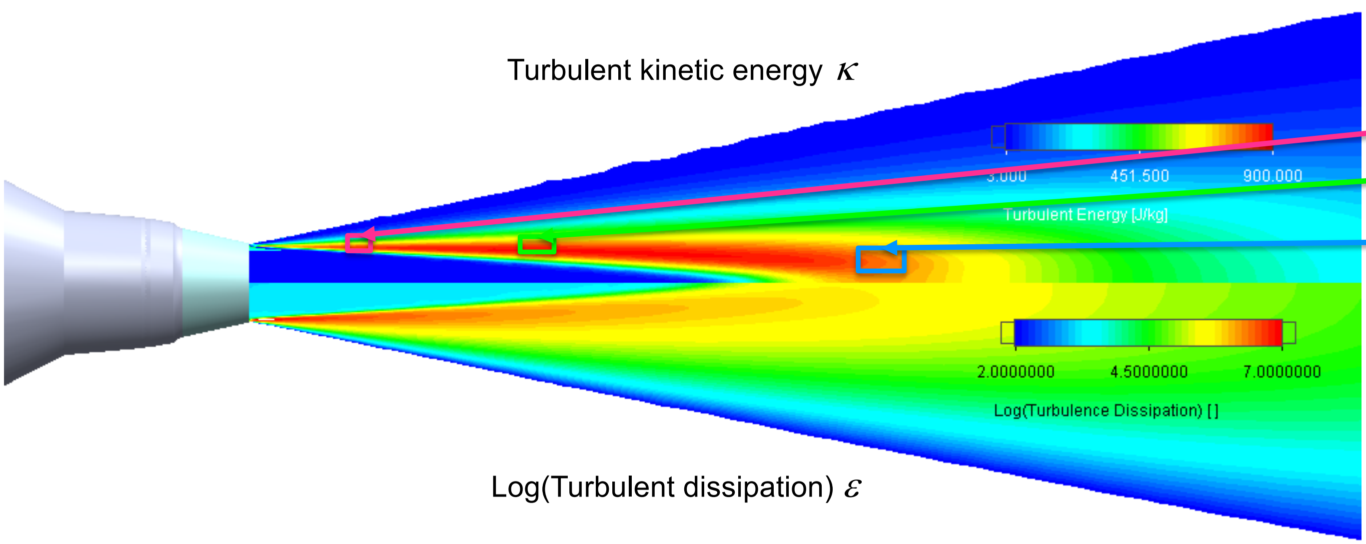


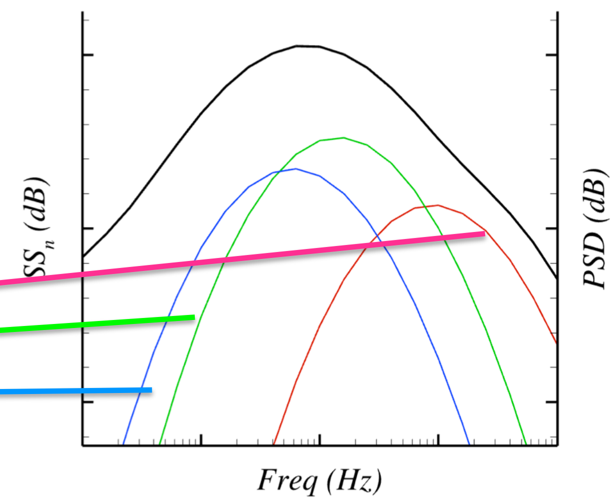


Small-scale source model development

- Assumption: ‘Small-scale’ noise contributed by independent sources SS_n

$$SS_n(f) \sim \kappa_n^{7/2}\, 10^{\left(-A\left(\ln\left(B\,\frac{\varepsilon_n/\kappa_n}{f}\right)\right)^2\right)} V_n$$





Small-scale source SS_n

- Both momentum SS_m and enthalpy SS_e source terms modeled (Khavaran 2009)
  - Enthalpy proportional to deviation of location temperature ratio relative to ambient, squared.

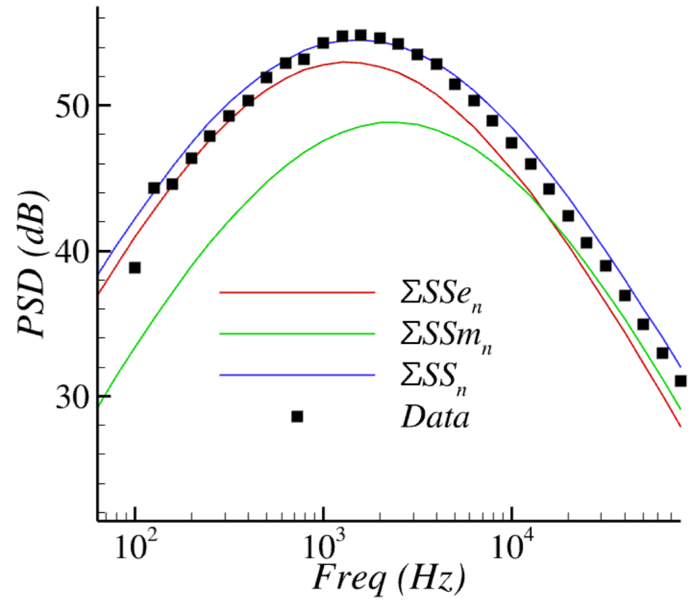
$$SS_n(f) = SS_{m_n}(f) + SS_{e_n}(f),$$

$$SS_{m_n}(f) = C_{ssm}\left(\frac{\rho_n}{\rho_\infty}\right)^2 \kappa_n^{7/2}\, 10^{\left(-A_{ssm}\left(\ln\left(B_{ssm}\frac{\varepsilon_n/\kappa_n}{f}\right)\right)^2\right)} V_n$$

$$SS_{e_n}(f) = C_{sse}\left|\frac{\rho_n}{\rho_\infty} - 1\right|^2 \kappa_n^{5/2}\, 10^{\left(-A_{sse}\left(\ln\left(B_{sse}\left(\frac{\rho_n}{\rho_\infty}\right)^{1/2}\frac{\varepsilon_n/\kappa_n}{f}\right)\right)^2\right)} V_n$$

- Take advantage of Greens function at 90° being nominally freespace.
- Coefficients $A_{ssm}, A_{sse}, B_{ssm}, B_{sse}, C_{ssm}, C_{sse}$ determined by trial and error fit to jet noise database at polar angle = 90°
- NASA SHJAR database for simple round nozzle (SMC000) covers
  - $0.5 < U/c_\infty < 1.5$,
  - unheated $< T_s/T_\infty < 2.7$.

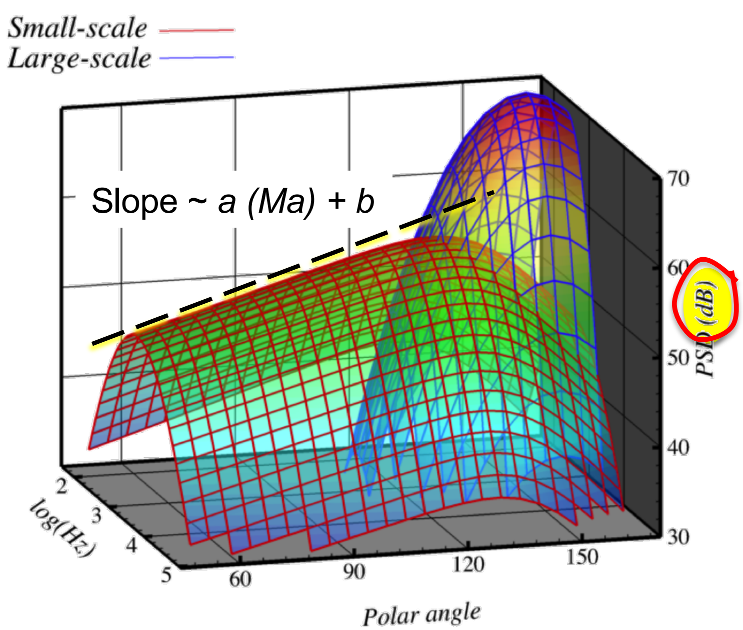
Ma = 0.9, *TsR* = 2.27

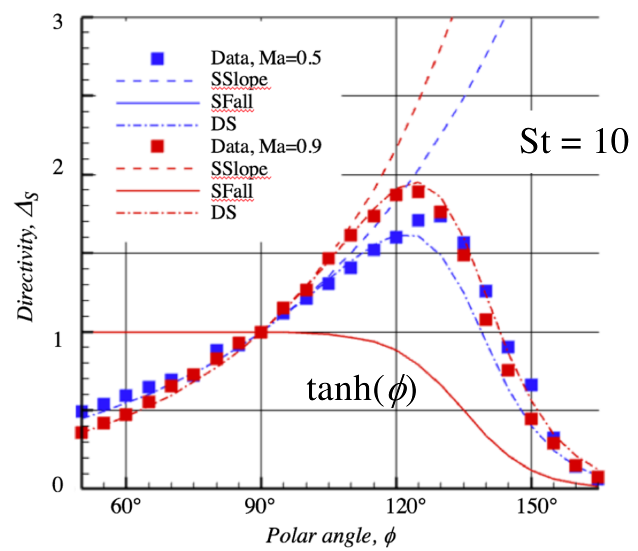


Small-scale directivity model

- Spectra anchored at 90°, derive directivity model for polar angle $\Delta_S(\phi) = PSD(f^*,\phi)/PSD(f^*, 90°)$

$$DS(\phi; Ma) = 10^{(a*Ma+b)*(\phi-90)} * 0.5 * \left(1 - \tanh\left(\frac{\phi - \phi_{s0}}{\phi_{s1}}\right)\right)$$

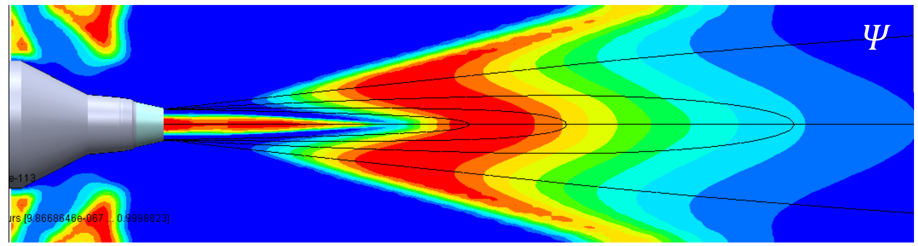




Large-scale source model

- Spatial filter Ψ to select TKE where lengthscales match dominant modes (~jet diameter):

$$\Psi(Djet) = 10^{\left(-\left(\ln\left(\frac{\kappa^{3/2}/\varepsilon}{Djet}\right)\right)^2\right)}$$



- Similar spectral model as small-scale source, different scaling with TKE

$$SL_n(f) = SL_{m_n}(f) + SL_{e_n}(f),$$

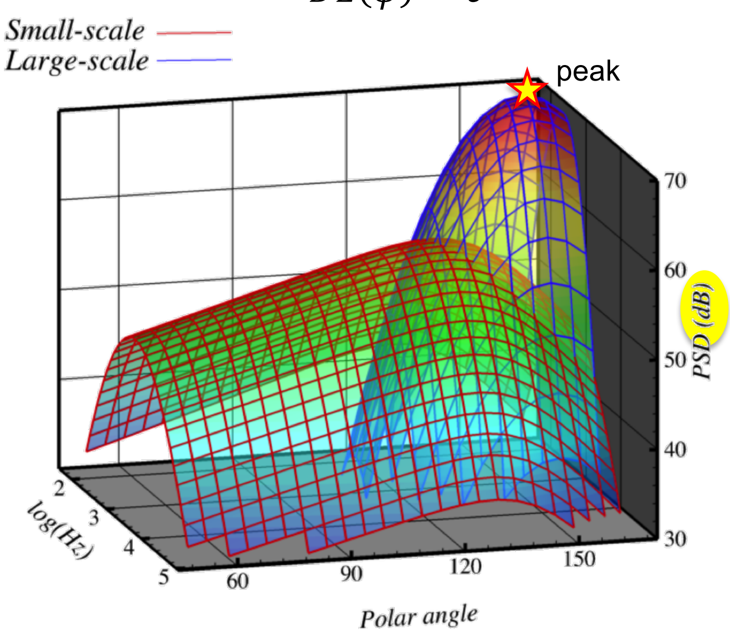
$$SL_{m_n}(f;Djet) = C_{slm}\left(\frac{\rho_n}{\rho_\infty}\right)\kappa_n^{9/2}\,10^{\left(-A_{slm}\left(\ln\left(B_{sl}\mathrm{m}\,\frac{\varepsilon_n/\kappa_n}{f}\right)\right)^2\right)}\,10^{\left(-\left(\ln\left(D_{slm}\left(\frac{\rho_n}{\rho_\infty}\right)\frac{\kappa^{3/2}/\varepsilon}{Djet}\right)\right)^2\right)}\,V_n,$$

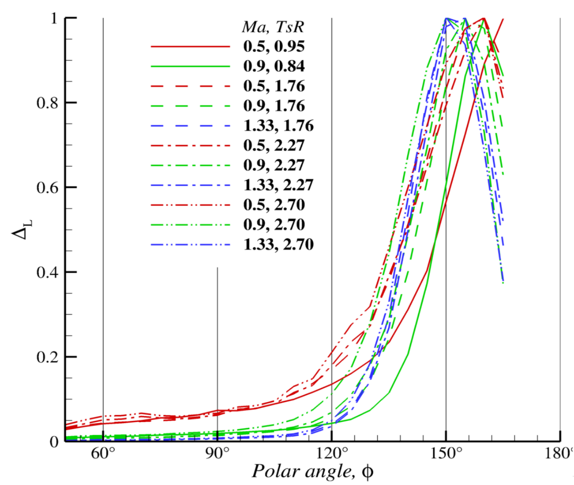
$$SL_{e_n}(f;Djet) = C_{sle}\left|\frac{\rho_n}{\rho_\infty} - 1\right|^2\kappa_n^{7/2}\,10^{\left(-A_{sle}\left(\ln\left(B_{sle}\,\frac{\varepsilon_n/\kappa_n}{f}\right)\right)^2\right)}\,\underbrace{10^{\left(-\left(\ln\left(D_{sle}\left(\frac{\rho_n}{\rho_\infty}\right)\frac{\kappa^{3/2}/\varepsilon}{Djet}\right)\right)^2\right)}}_{\Psi(Djet)}\,V_n$$

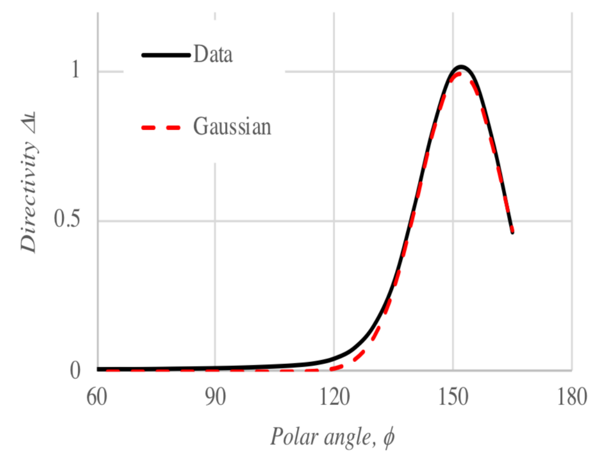
Large-scale directivity model

- Dramatic directivity is hallmark of large-scale source $\Delta_L(\phi) = PSD(f_{peak}, \phi)/PSD(f_{peak}, \phi_{peak})$
- ϕ_{peak} dependent on Ma, Ts/T_∞ -- obtain from integral measure of jet plume.
- Reasonable fit by Gaussian in ϕ

$$DL(\phi) = e^{-\left(\left((\phi-\phi_{l0})/\phi_{l1}\right)^2\right)} \qquad \phi_{l0} = -11(Ma-1) - 4\left(TsR_{ref} - 1\right) + 158$$

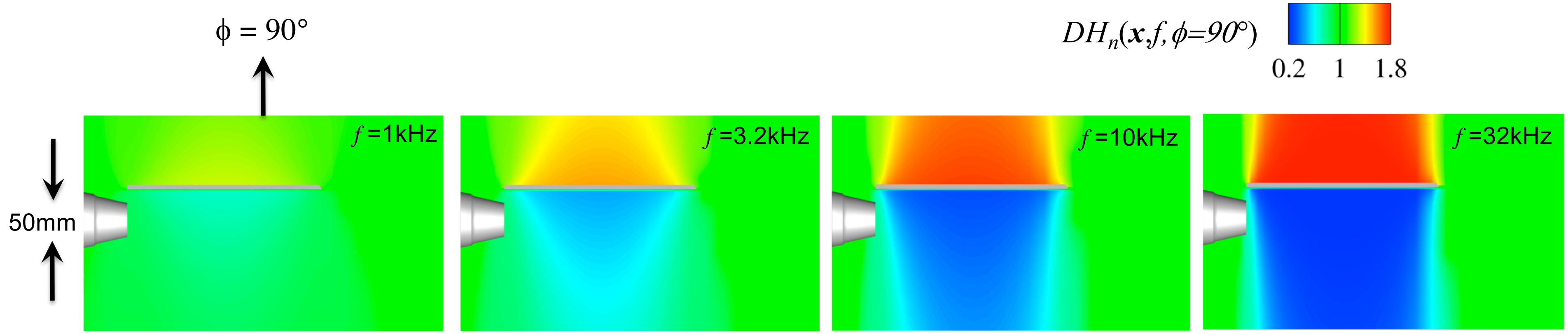






Directivity modified by solid surfaces

- Shielding/Reflection of source behind planar surface estimated by method of Maekawa (1968)
- Assumes no flow!
- *DH* is attenuation factor relative to free-space Green's function.



Total Model

- Contribution of each n^{th} cell in CFD RANS solution to far-field noise:

$$PSD3(x,y,z,f,\phi) = DS(\phi)\sum_n SS_n(x,y,z,f)\, DH_n(x,y,z,f,\phi) + DL(\phi)\sum_n SL_n(x,y,z,f)\, DH_n(x,y,z,f,\phi)$$

3-D source density to observer ϕ at frequency f

$$PSD2(x,y,f,\phi) = \int PSD3(x,y,z,f,\phi)\, dz$$

Phased array view of source distribution

$$PSD1(x,f,\phi) = \int PSD2(x,y,f,\phi)\, dy$$

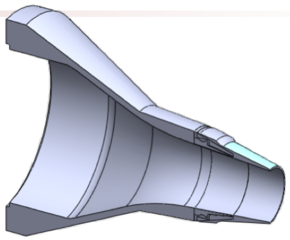
Axial source distribution

$$PSD(f,\phi) = \int PSD1(x,f,\phi)\, dx$$

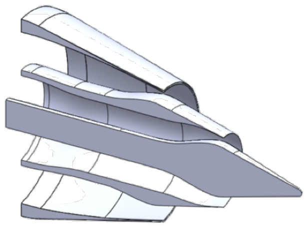
Spectral directivity of far-field noise

Validation

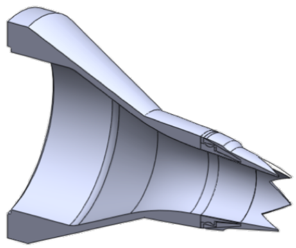
- Single-stream jets of various temperatures



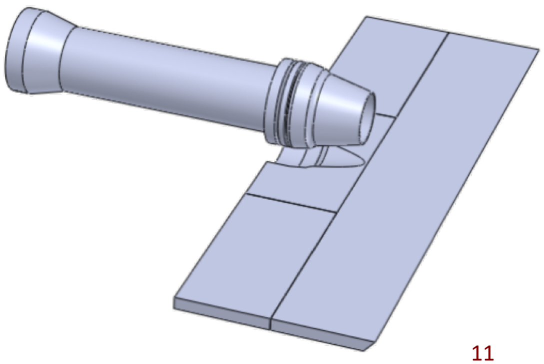
- Dual-stream coaxial jets with heat



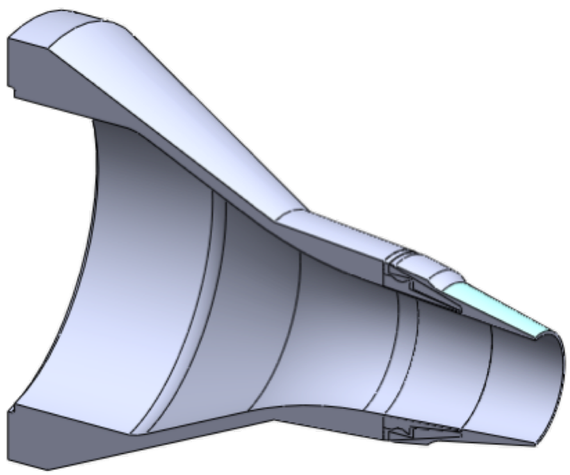
- Single-stream jets from nozzles with enhanced mixing features



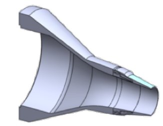
- Jets in proximity to surfaces (excluding the edge-induced noise).



Simple round jets, single-stream, no plug; heated

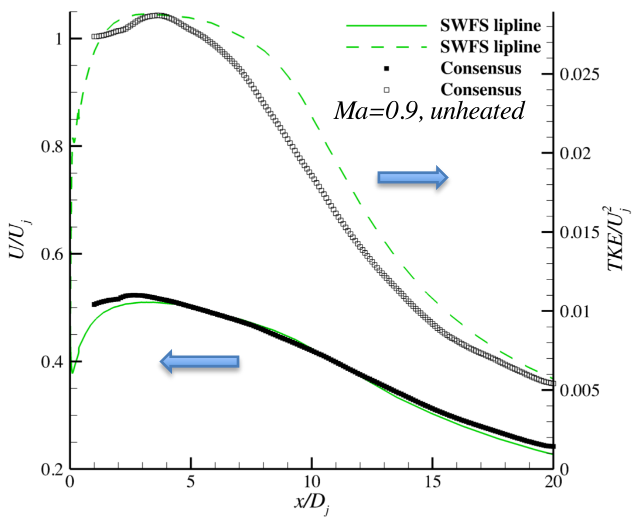


Single-stream round hot jets



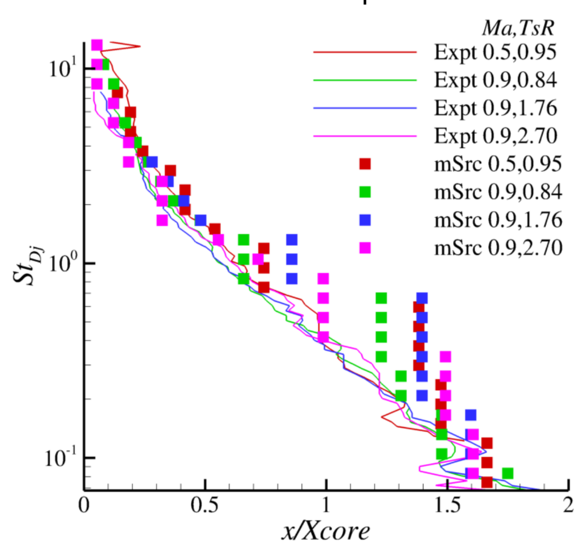
- Tanna matrix: 0.5 < *Ma* < 1.8; unheated < *TsR* < 2.7
- RANS using Mentor Graphics cartesian mesh method (SolidWorks Flow Simulation)

RANS vs PIV--lipline



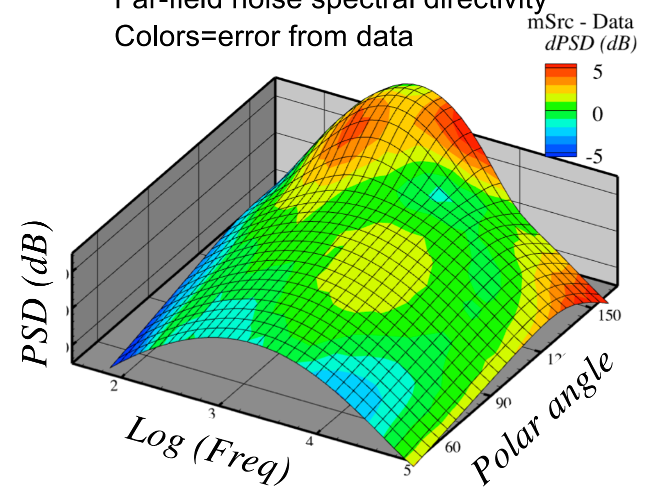
Bridges, J., and Wernet, M. P., "The NASA Subsonic Jet Particle Image Velocimetry (PIV) Dataset,"

Source distributions--peak locations



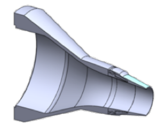
Podboy, G. G., "Jet-Surface Interaction Test: Phased Array Noise Source Localization Results,"

Far-field noise spectral directivity
Colors=error from data

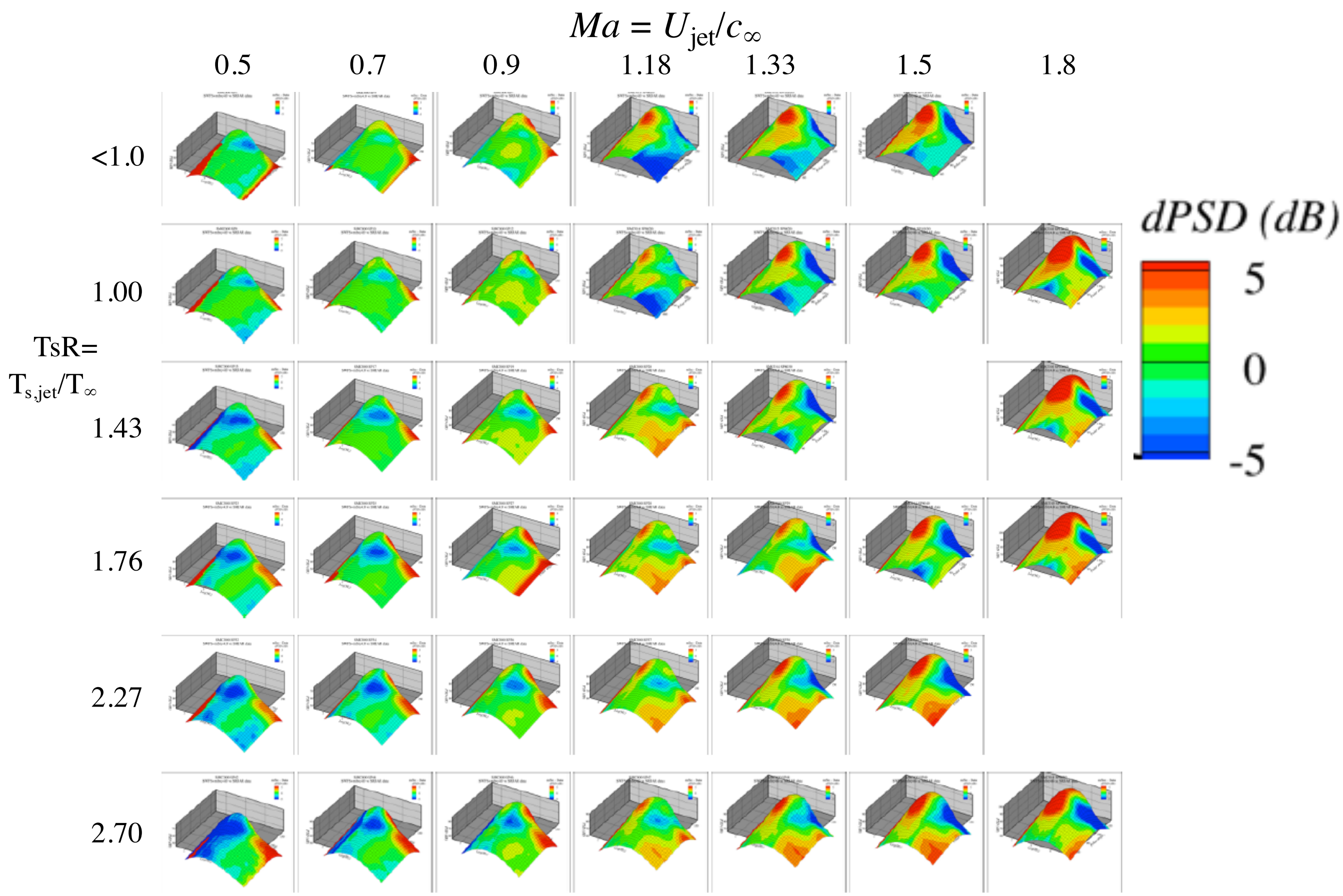


Single-stream, shock-free round hot jets

Absolute error in far-field spectral directivity

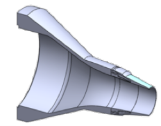


- *mSrc* model works better than empirical models over large range of *Ma, TsR* where *TsR* < 2, *Ma* < 1.2
- Suffers errors in predicting peak frequency at supersonic conditions
- Overpredicts far aft angles
- Transition between small- and large-scale (blue dot) worse at high temperatures.

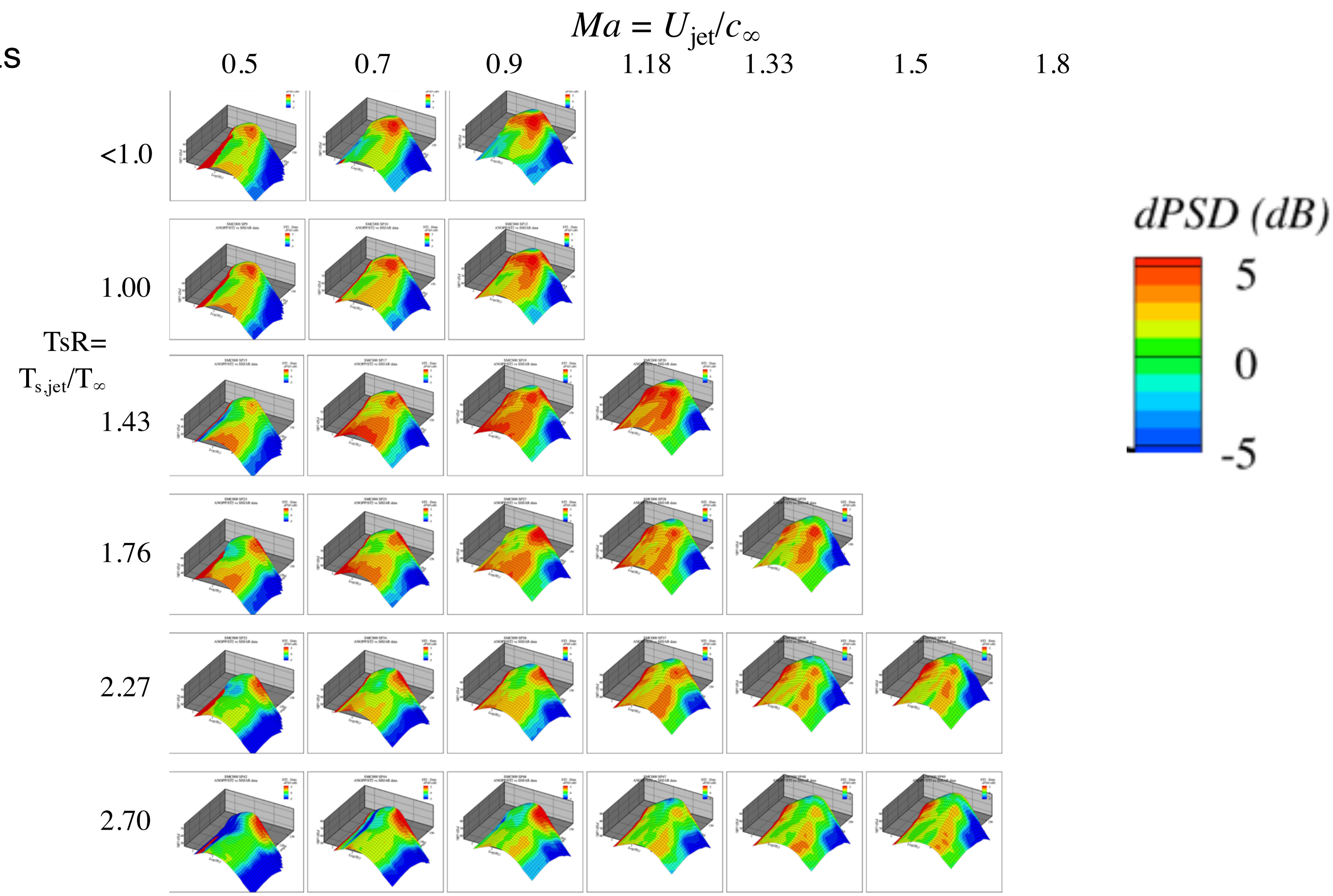


Brown, C. A., and Bridges, J., "Small Hot Jet Acoustic Rig Validation,"

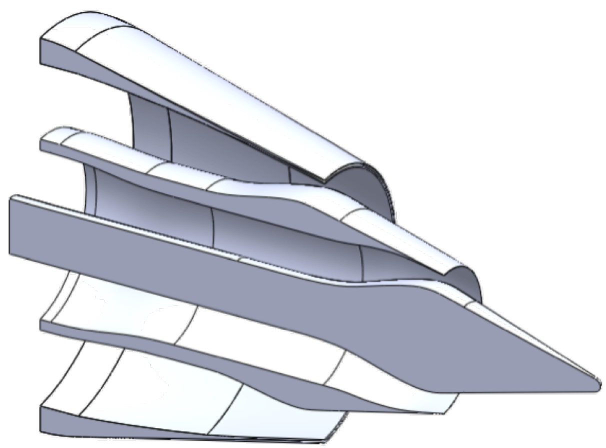
Single-stream, shock-free round hot jets
Absolute error in far-field spectral directivity



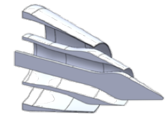
- ANOPP/ST2 empirical model has greater errors relative to SHJAR database.



Coaxial dual-stream, separate flow, with plug; hot core

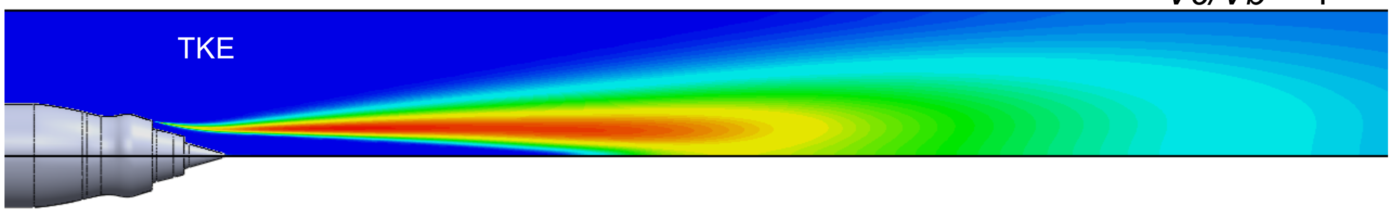


Dual-stream jets
Computed flow fields

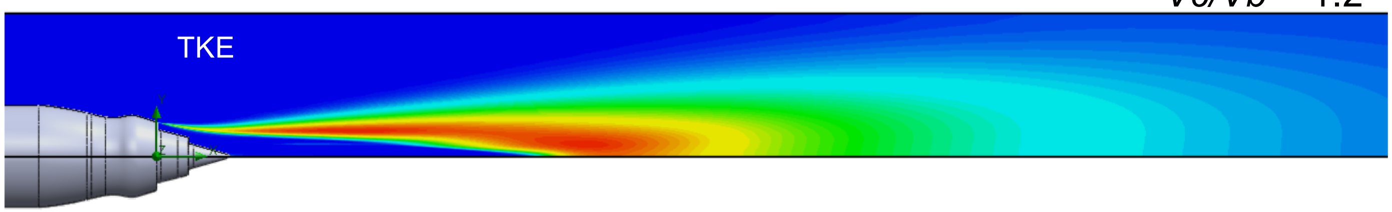


- Differences in turbulence of single- and dual-stream jets, plugged nozzles
- Peak TKE shifts downstream with increasing velocity ratio

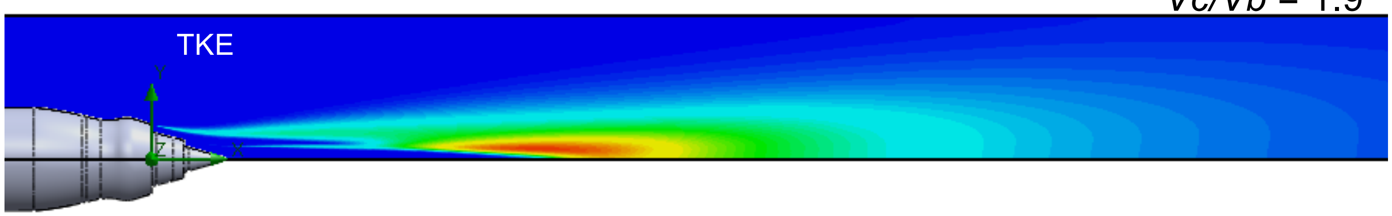
Vc/Vb = 1



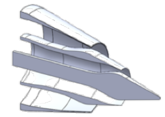
Vc/Vb = 1.2



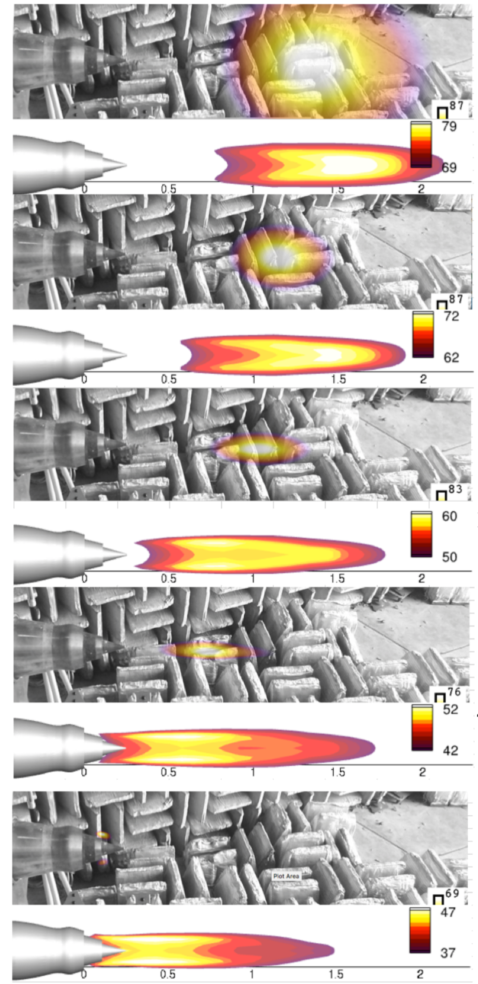
Vc/Vb = 1.9



Dual-stream jets
Source distributions



- Comparison of PSD2 with phased array data for axisymmetric dual-stream jet with external plug
- Similar distributions, except at high frequency where phased array finds source more tightly focused around plug
  - Need better Green's function for plug nozzle?

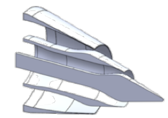


Vc/Vb = 1.2.
ϕ = 90°

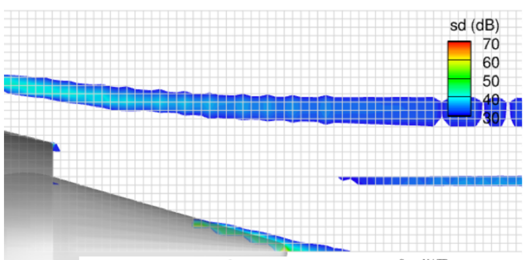
Bridges, J. E., Podboy, G. G., and Brown, C. A., "Testing Installed Propulsion For Shielded Exhaust Configurations,"

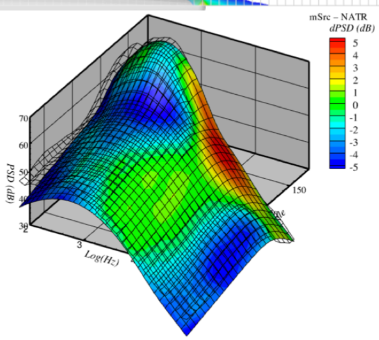
Dual-stream jets

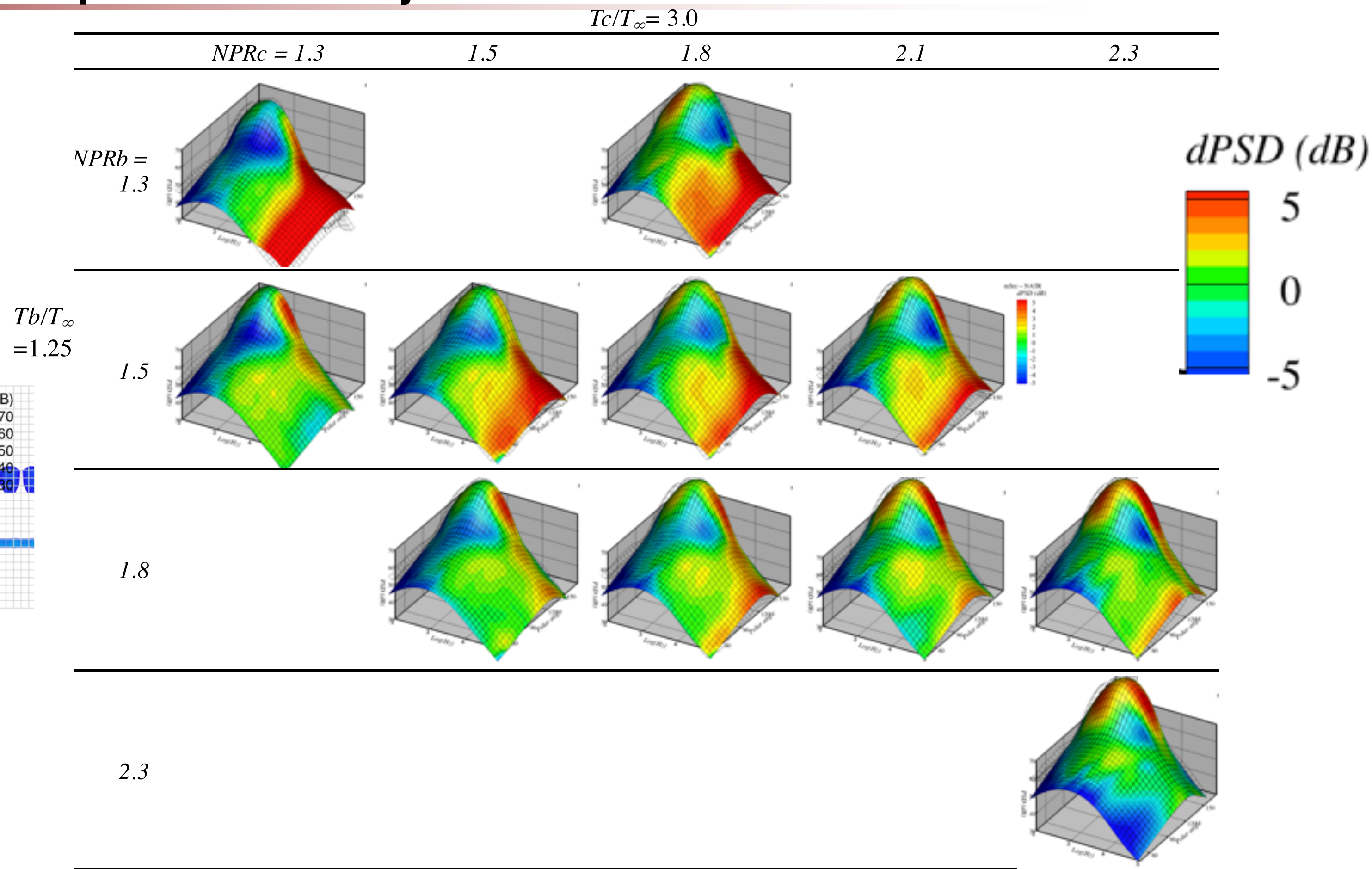
Absolute error in far-field spectral directivity



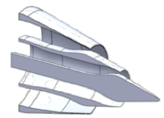
- Cases cover
  1.25 < *Vc/Vb* < 2.3
- Generally within ±2dB
- Underpredicts low freq
- Overpredicts high freq
  – Wrong TKE on plug?



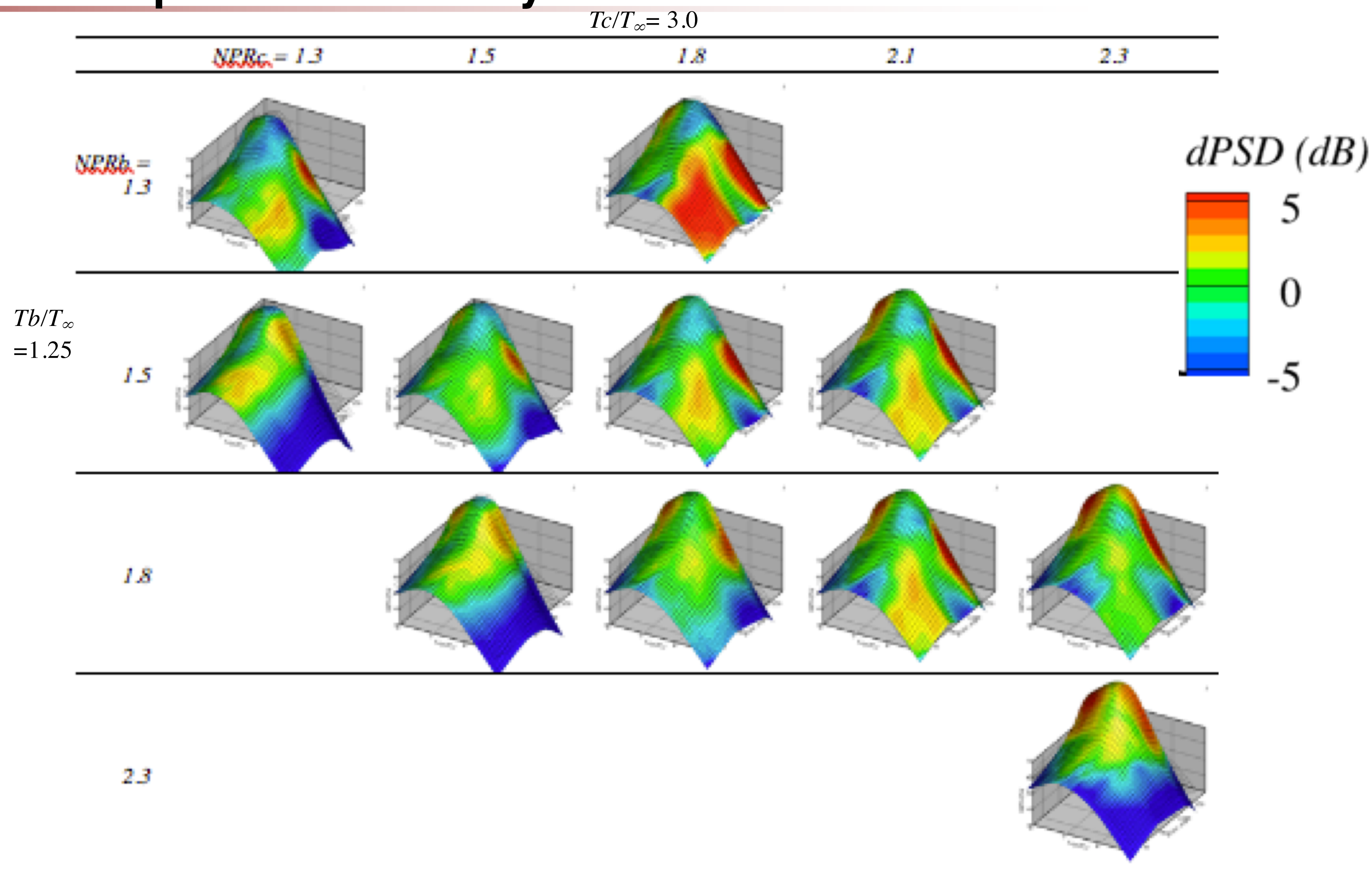




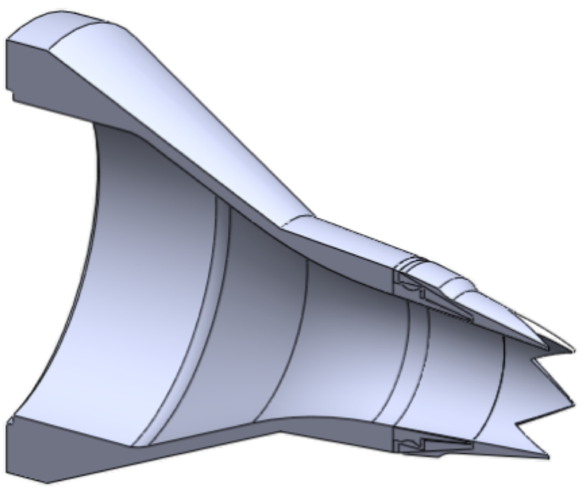
Dual-stream jets
Absolute error in far-field spectral directivity



- ANOPP/ST2 empirical model has comparable errors relative to NATR database.
- Underpredicts high freq
- Why?

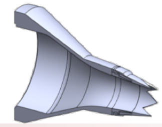


Chevron jets, single-stream, no plug

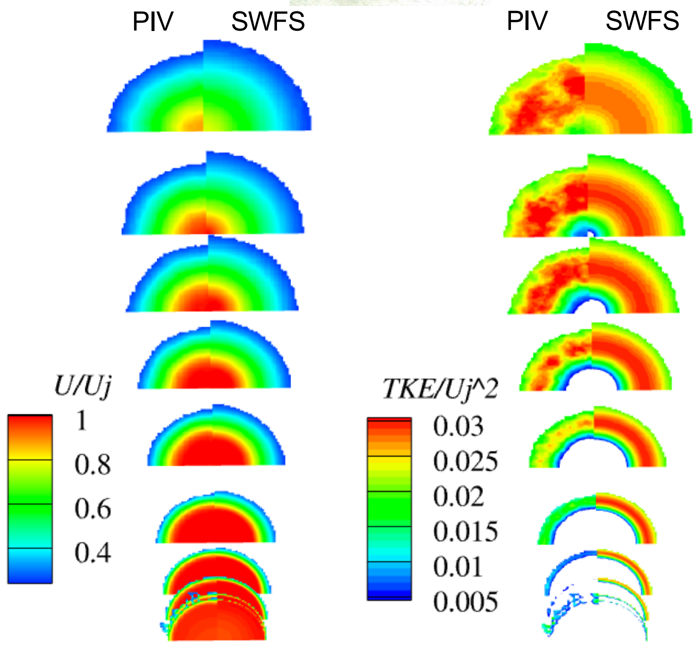


Simple chevron nozzles

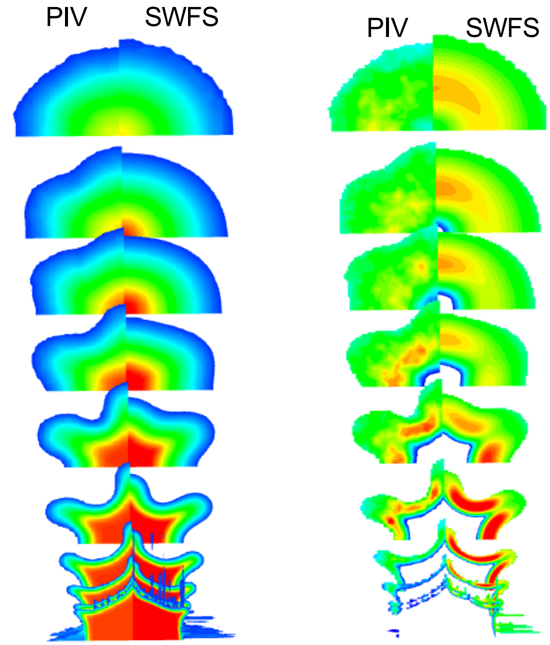
CFD validation



SMC000



SMC001

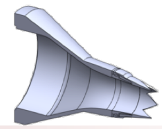


RANS accurately predicts change in TKE distribution, especially near chevrons

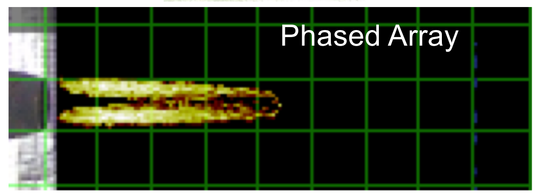
Opalski, A., Wernet, M., and Bridges, J., "Chevron Nozzle Performance Characterization Using Stereoscopic DPIV"

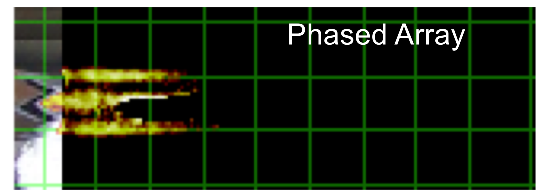
Simple chevron nozzles
Acoustic validation

- Source distributions for round and chevron nozzles:
  - mSrc picks up change in spatial distribution of high frequency noise generated by chevrons
- Far-field noise:
  - mSrc does not predict as much high freq increase/low freq reduction as experiment.
- Since TKE amplitude and source location seem correct, possibly efficiency of TKE-->acoustic energy is off.
  - Chevrons change anisotropy of TKE

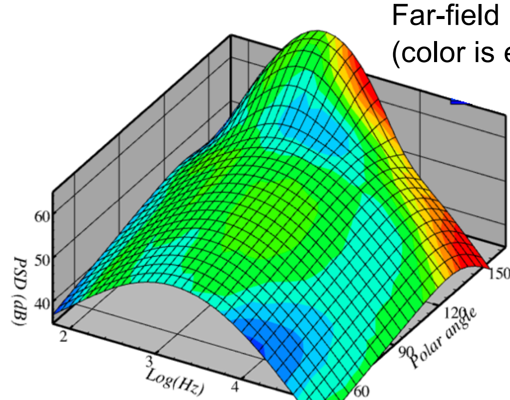


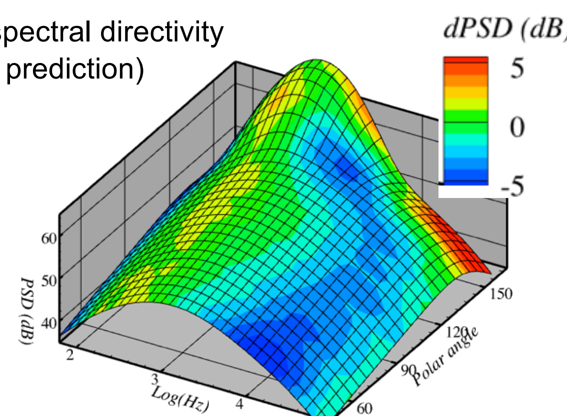
Ma=0.9, unheated





Far-field noise spectral directivity
(color is error in prediction)

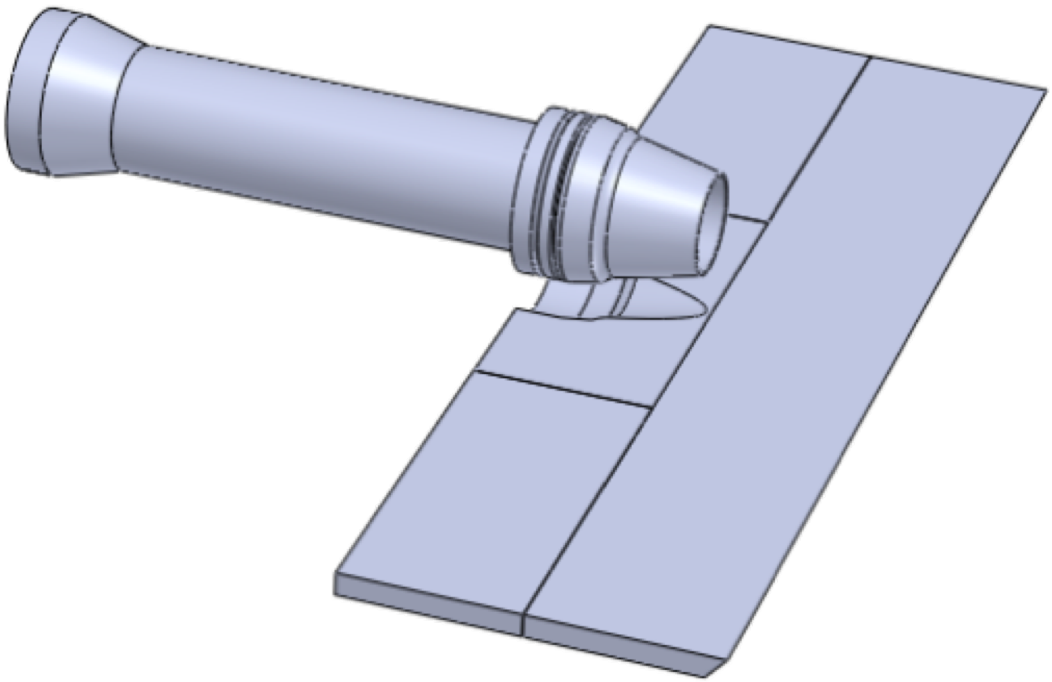




Dougherty, R. P., and Podboy, G. G., “Improved Phased Array Imaging of a Model Jet”

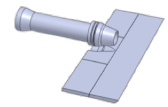
Bridges, J., and Brown, C., “Parametric Testing of Chevrons on Single Flow Hot Jets,”

Installed jets, single-stream, no plug

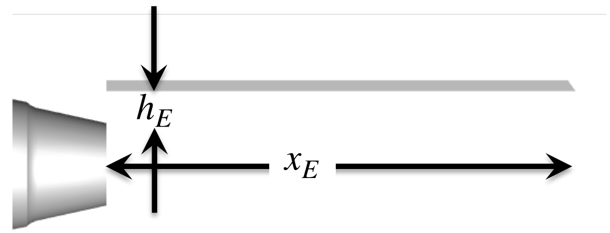


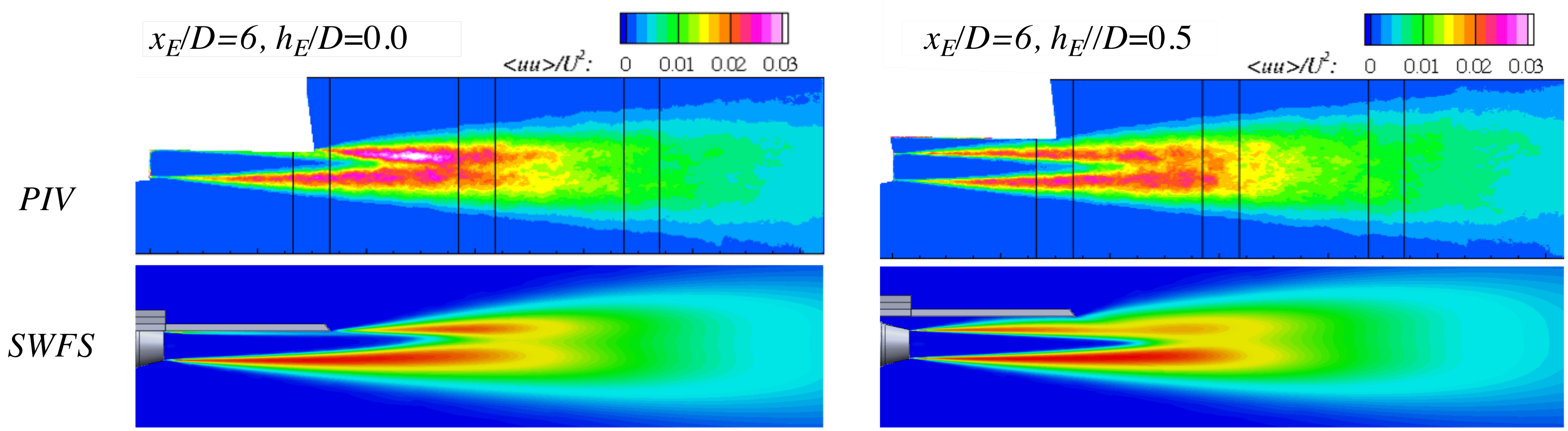
Jet-Surface Interaction

CFD validation



- Check on validity of mSrc's shielding/reflection model
- Will not predict scattering of turbulent energy into sound by trailing edge of plate.
- SWFS, like other RANS codes, generally predicts TKE of jet near plate well, but underpredicts TKE aft of plate when jet is on the plate.

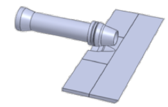


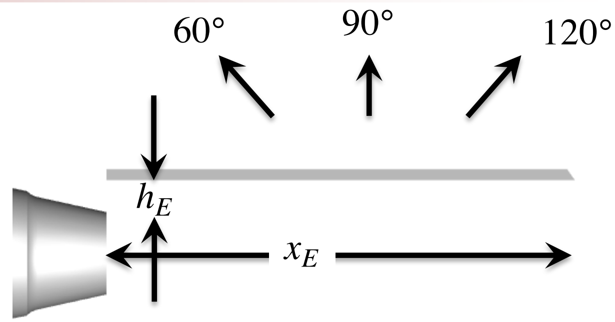


PIV: Brown, C. A., and Wernet, M. P., "Jet-Surface Interaction Test: Flow Measurement Results"

Jet-Surface Interaction

Acoustic validation

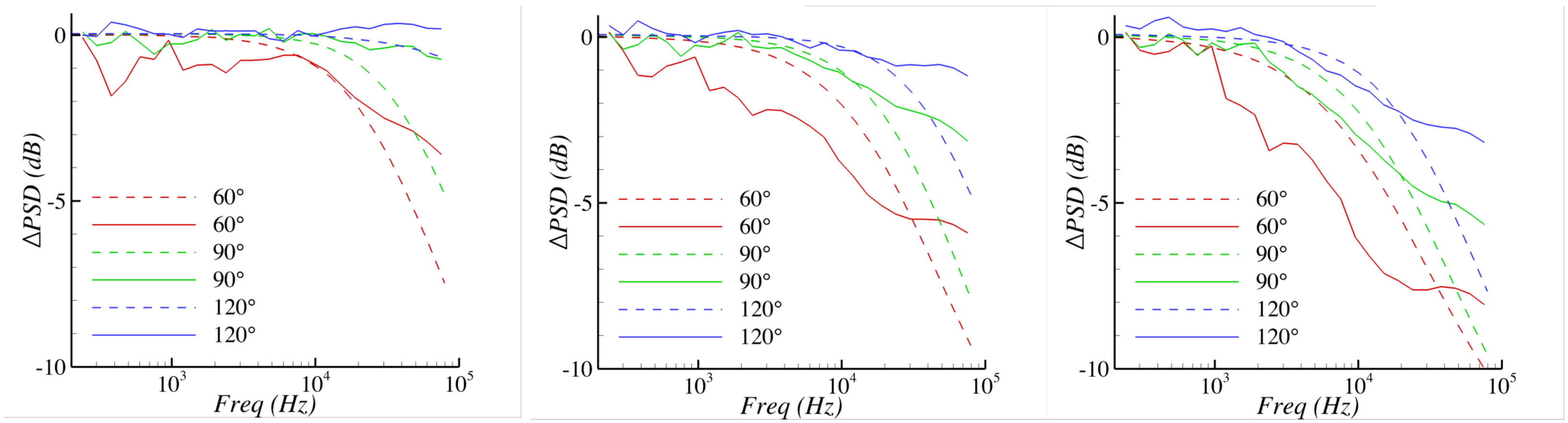




- Difference in far-field noise from Ma=0.9, unheated jet, without minus with surface.
- Shielding is overpredicted at highest frequencies, but within 2dB for most frequencies of interest.
- Be suspicious of shielding > 5dB!

mSrc - - - -
Expt ——

D=50mm

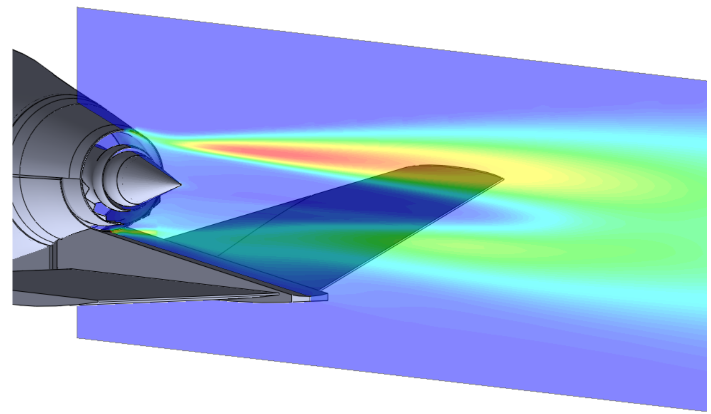


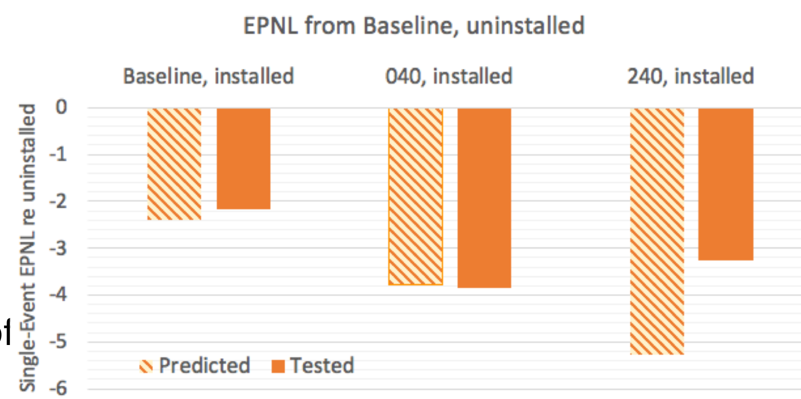
$x_E/D=2$ $h_E/D=2.5$ | $x_E/D=4$ $h_E/D=2.5$ | $x_E/D=6$ $h_E/D=2.5$

Brown, C. A., "Developing an Empirical Model for Jet-Surface Interaction Noise,"

Summary

- *mSrc* is robust numerical model to be used with RANS to predict installed jet noise.
  - Can be traced to acoustic analogies, but developed empirically.
  - Uses simple models for Green’s function for speed, robustness.
- Assumptions/Limitations
  - Axisymmetric sound field
  - Shock-free jets
  - No scattering of TKE into sound by edges
- Accurate to ±2dB for most applications studied.
- Provides intermediate, diagnostic results
- Works with any RANS code.
- When coupled with SolidWorks™ Flow Simulation RANS solver, *mSrc* can provide jet noise prediction from geometry within few hours on laptop computer.
- Used in designing installed nozzle concepts for exploration of integrated low-noise propulsion systems.





Bridges, J. “Noise measurements of a low-noise top-mounted propulsion installation for a supersonic airliner”